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AUTONOMOUS LIQUID ENCAPSULATED CZOCHRALSKI (LEC) GROWTH OF SINGLE CRYSTAL GaAs BY "INTELLIGENT" DIGITAL CONTROL

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AUTONOMOUS LIQUID ENCAPSULATED CZOCHRALSKI (LEC) GROWTH OF SINGLE CRYSTAL GaAs BY "INTELLIGENT" DIGITAL CONTROL

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EXECUTIVE SUMMARY

* Total automation of high-pressure LEC GaAs crystal growth is reported.
* Supervision time, of a 4 kilo GaAs crystal growth run, is reduced from 20 hours to 10 minutes.
* Large yield improvements in growing single GaAs crystals are obtained.
* Precision diameter control during crystal growth is reported which results in higher wafer yield after ingot grinding and slicing.
* A new control system utilizing heuristic control features is described.

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AUTONOMOUS LIQUID ENCAPSULATED CZOCHRALSKI (LEC) GROWTH OF SINGLE CRYSTAL GaAs BY "INTELLIGENT" DIGITAL CONTROL

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ABSTRACT:

Virtually total automation of the high-pressure LEC process for GaAs growth could be achieved with an "intelligent" growth control approach which combines deterministic and heuristic techniques. A number of 4 kg, 3 inch semi-insulating GaAs crystals have been grown reproducibly on an adapted Cambridge Instruments CI 358 puller without any significant operator intervention; even complex process steps like seeding and tail-off could be successfully handled by the system on its own. Process yields of more than 75 percent single crystals could be accomplished. Crystals grown with the digital system were superior in uniformity and diameter control, compared to conventionally grown crystals.

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1. Introduction

The first attempts towards automating the Czochralski crystal growth process, and, particularly, the growth of III-V compound crystals, date back to the early 1970s [1],[2],[3]. All these early techniques, up to more recent ones [4],[5], have in common an essentially deterministic approach, i.e., a more or less rigidly pre-defined profile of process parameters which the system tries to maintain as a function of time or crystal length.

However, the Czochralski technique involves extremely complex thermodynamic processes: The flow patterns of the semiconductor melt in the crucible may change spontaneously and unpredictably [6]; even the most elaborate computer simulations can only indicate the possibility of such changes but can hardly be used to predict the time of their actual occurrence. (Computer simulations do contribute to a better understanding of the growth process, though, and they can aid the design of advanced process controllers [7].) Since even minor variations of the convective flow in the semiconductor melt are liable to influence the temperature distribution at the solidification interface, and hence the amount of material solidified, they result in fluctuations of the diameter of the crystal grown which have to be compensated for by the process controller. This can be accomplished by a conventional system which applies more or less linear closed-loop control of the crystal diameter, for example, by means of a PID (Proportional-Integral-Derivative) controller approach. However, the gain of such a controller has to be chosen relatively high in order to enable it to cope with the spontaneous process disturbances, which entails that smaller fluctuations, e.g., due to random noise imposed on the measured diameter, have an undesirable influence on the process, introducing a continuous variation of the process parameters and according fluctuations of the crystal properties. The resulting tendency of a conventional controller to either overreact to artifacts, or to underact to genuine process deviations, has to be compensated for by an additional intelligent control loop. In all "automated" crystal growth controllers designed in the past, this loop had to be closed externally, over a human crystal growth operator.

Although the features of commercial "automated" crystal growth controllers certainly constitute a significant help for the operator, it is nevertheless still the operator whose skill and experience determine the quality of the crystals grown. This human interaction leads inevitably to a deterioration of the reproducibility of the process, and it constitutes a serious obstacle to the large-scale growth of high quality crystals.

The system developed at Arizona State University (ASU) features, in contrast, novel heuristic control approaches which enable it to execute operations automatically which had to be initiated or entirely carried out by the operator on the earlier "automated" Czochralski pullers. Heuristic control is accomplished basically by emulating the decisions within the digital controller which were otherwise made by a human operator, which entails facilities akin to artificial intelligence. Since a computer-based system can be designed to react faster and much more reproducibly than a human being, especially if its knowledge base is not changed significantly, the reproducibility of the process controlled by it is intrinsically superior to conventional approaches.

2. The Control Of The LEC Process

The system presented here was implemented on an adapted Cambridge Instruments CI-358 high-pressure puller whose essential components (barring the high-pressure vessel) are shown in Fig. 1.

The operation of a Czochralski puller requires the following parameters to be controlled during the synthesis and growth process:

* Heater temperature. (Some advanced approaches use multi-zone heaters in order to tailor the heat distribution

within the hot zone, which entails that three or more heaters have to be controlled independently.)

* The speeds of the four motors for seed and crucible lift and rotation.

* The chamber pressure.

* Auxiliary functions like cooling water supply, gas exhaust system, and so on.

For reasons of simplicity, the system developed at ASU was restricted to the control of the four motors, and of up to three heater zones. Including gas pressure control and auxiliary functions would not have imposed a problem for the design of the digital controller, but it was not considered necessary for a prototype whose essential purpose was to demonstrate the feasibility of autonomous LEC growth.

Controlling a crystal growth process is not an entirely unambiguous task: Many parameters, some of them even conflicting, determine the quality of a gallium arsenide crystal:

* Electrical properties like conductivity type, and free carrier density, mobility, and lifetime.

* Crystallographic properties like orientation, dislocation density, and local dislocation distribution.

* Processing requirements like yield and crystal diameter control.

In fact, the only parameter which can be controlled directly (and on which all crystal growth process control schemes concentrate) is the diameter of the crystal. For compound semiconductors, the diameter of the growing crystal is usually determined from the increase of the crystal's weight with time [8],[9]; even the latest commercially applied diameter control approaches (including ASU's) are based on the weighing method, although efforts are being made to use advanced optical or X-ray techniques for in situ crystal diameter measurements [10]. The currently grown diameter of the crystal can be controlled by a variation of the heater temperature; a temperature increase reduces the diameter, and vice versa. Similarly, diameter control could also be effected by a modulation of the pull rate. This approach is widely used in silicon Czochralski growth; it is not feasible for the growth of gallium arsenide because the concentration of impurity levels and therefore the crystal's electrical properties depend crucially on the growth rate [11].

While it is possible, at least within certain limits, to measure and control in a closed-loop mode the diameter of the crystal grown, no closed-loop control is possible for all the other parameters listed above. Crystals with the desired electrical and crystallographic qualities can only be obtained from a careful analysis of crystals grown under conditions monitored as closely as possible, and by accurate reproduction of growth conditions yielding crystals with the intended properties. This requires not only a very intimate knowledge of the events during a growth run and of the resulting crystal quality, but also, in addition, a very precise reproduction of crucial process sequences. Both demands, high-volume data recording and exact process control, can only be met by a highly automated, operator-independent growth technique.

A comprehensive analysis of the growth process involves measuring and recording as many growth related parameters as possible through an entire growth run. Hence, the following data are measured or calculated, displayed on the console terminal (Fig. 2), and optionally recorded on disk by the digital controller presented here:

* The setpoints for the speeds of the four motors, and for the temperatures of up to three heater zones.

* The calculated crystal diameter.

* The temperatures of up to three heater zones, and the "base" temperature at the bottom of the crucible.

* The electric power supplied for up to three heaters, and the corresponding setpoints generated by the controller.

* The speeds of the four motors for seed and crucible lift and rotation.

* The current positions of the seed and the crucible.

* The weight of the crystal, and its first derivative with respect to time.

* The gas pressure inside the growth chamber.

* The output of a "contact device" which gives a value related to the electrical conductance between the seed and the semiconductor melt. This parameter is used in the initial stages of crystal growth, particularly during seeding, to determine whether a positive contact was established between the seed and the melt and crystal growth has started or failed.

Furthermore, the ASU system has provisions to record eight additional analog input signals for special growth experiments.

3. The Design Of The Czochralski Growth Control System-Hardware

ASU's Czochralski Growth Control System (CGCS) is based on an eight-bit microcomputer consisting of standard OEM (Original Equipment Manufacturer) boards. The performance of its Intel 8085-2 CPU is enhanced by the addition of a numeric processor (Intel 8231) which improves the throughput for floating-point calculations. The system utilizes the full 64 KBytes addressable memory space of the 8085 with 56 KBytes of RAM and two switchable 8 KBytes banks of ROM. Two industrial standard, single-side, single-density 8" floppy disk drives serve as a mass storage for programs, program overlays, and data. The interface to the puller consists of a 32 channel A/D converter with 16 bits resolution for the input signals, and of a 16 channel D/A converter with a resolution of 12 bits for the analog output of the CGCS. A number of digital input and output lines read switches and set relays, e.g., for the control of the rotation directions of the four motors. A CRT terminal, a matrix printer, and a multi-channel chart recorder serve as an interface to the operator (Fig. 3).

The digital controller is designed to have its inputs connected in parallel to the inputs of the existing conventional analog controller. Both systems can therefore monitor the process simultaneously. A digital output signal supplied by the CGCS allows to replace the analog controller's outputs with the outputs of the CGCS (Fig. 4). This approach permits to monitor runs with the digital system which are controlled by the analog controller, and it allows to fall back to the analog controller if necessary. (Although there is no need to run the puller with the analog system once the digital controller has been tuned, this approach proved to be very helpful during the early stages of the implementation of the digital controller.)

The digital controller interfaces to the puller via analog signals which serve as motor speed and heater power setpoints. The final control of the actual motor speeds and of the heater SCR(s) is done by the pertinent hardware of the analog system.

4. The Design Of The Czochralski Growth Control System-Software

4.1 The Operating System Environment

Real-time process control as done with the CGCS requires, in general, the ability to execute control tasks asynchronously whenever they are required. Consequently, a real-time operating system (Intel's iRMX-80) was chosen for the CGCS computer. Based upon the experiences made with an earlier similar system [12],[13], great pain was taken to design the growth control computer as a stand-alone unit. The ability to run a digital controller in a stand-alone mode entails the availability of certain utility functions (e.g., disk formatting and file maintenance), and, if possible, the ability to execute auxiliary programs. Since these functions were not straightforwardly obtainable from iRMX-80, an operating system emulator was designed which permits to run commercially available or already existing software for Intel's development system environment ISIS-II. The software thus implemented on the CGCS computer comprises, in addition to the mentioned utilities, a BASIC interpreter, and a full-screen text editor. Furthermore, several auxiliary programs were designed for displaying and editing the disk files created or needed by the CGCS; they are based on this emulated operating system environment as well. The control computer comes up under the operating system emulator; the actual Czochralski Growth Control software is invoked and executed as one of many available programs. Since the total size of the actual growth control program exceeds by far the computer's memory space, an elaborate overlay approach had to be designed which loads program modules from disk into memory only when and while they are being used.

4.2 Basic Operation Of The Czochralski Growth Control System

Since the implementation of the CGCS was planned as a gradual replacement of the standard analog controller of the puller, the primary target was to emulate the basic operation of the analog controller with the digital system. Therefore, conventional closed-loop control methods were applied for the fundamental operations, namely, for the control of the speeds of the four motors for seed and crucible lift and rotation, and of the power supplied to the heater or heaters.

Closed-loop control in the CGCS is generally based on PID controllers which are realized with a generic PID routine. This routine is invoked with dedicated parameters for each control loop. In addition to standard proportional, integral, and derivative control, the generic PID controller features several modes of output limiting and "windup" protection (which enhances its dynamic response if the controller incurs a limit condition); the possibility to add a bias value to the output of the PID controller allows for feed-forward operations, and for small corrections of setpoints which are basically determined by other sources.

The standard control loop for each of the four motors is shown in Fig. 5: The primary control of the motors is done by the analog circuitry which came with the Cambridge Instruments controller. Under digital control, the setpoint for these analog motor controllers is supplied by the D/A converter outputs of the CGCS, rather than from a potentiometer on the analog console. Basically for the compensation of nonlinearities and offset errors of the analog motor controllers, digital PID loops are used to pre-process the signals finally submitted to the analog system in order to make the actual speeds exactly match their corresponding setpoints. A combined feed-forward and PI control approach can be used to optimize the performance of the entire control loop. (Using an analog hardware-based rather than a digital software-based technique for the primary motor control guarantees a sufficiently smooth and fast operation without overburdening the digital system.)

With regard to the diameter control technique generally applied to the growth of compound semiconductors, temperature and diameter control are closely related to one another (Fig. 6): In "manual" mode, i.e., without closed-loop diameter control, a temperature setpoint value is compared to the digitized output of the thermocouple which monitors the temperature of the heater; the resulting difference is submitted to a PID controller whose output controls the power setpoint of the analog heater SCR controller. In "automatic" closed-loop diameter controlled mode, the heater temperature setpoint is modified by the output of a superimposed diameter control loop. In contrast to the standard Cambridge Instruments diameter controller which controls the heater temperature according to the deviation of the first derivative of the crystal weight ("differential weight") from a given setpoint, the CGCS first calculates the actual crystal diameter, and uses it as an input to the diameter controller. This permits a more straightforward and understandable operation of the controller. Since the CGCS was designed for up to three heater zones, three independent temperature and diameter controllers according to Fig. 6 have been provided in the program.

An auxiliary control loop can optionally be applied to the vertical speed of the crucible: Since the level of the semiconductor melt in the crucible drops during a growth run according to the amount of material solidified, the interface between the solid crystal and the melt would change its position within the heater, which is liable to cause growth instabilities, unless the crucible is lifted exactly by the amount of the melt drop. On conventional pullers, the crucible lift speed is set to a fixed value which is calculated under the assumption of an ideally cylindrical crystal with constant diameter. The CGCS, in contrast, computes a setpoint value for the crucible position as a by-product of the diameter evaluation routines, essentially by determining the amount of melt already used up by the crystal; this setpoint is compared to the actual crucible position, and the resulting error signal is used as an input for a PID controller whose output is superimposed on the crucible speed setpoint (Fig. 7).

The actual diameter of the crystal, and a number of auxiliary parameters like the crucible position setpoint, the growth rate, and the crystal length grown, are calculated by the CGCS once every ten seconds. In addition to the differential weight, several other measured parameters are used as inputs for these computations, as shown schematically in Fig. 8. The diameter evaluation takes into account the buoyancy of the part of the crystal immersed in the boric oxide encapsulant; for the diameter controller parameters used in our implementation, meniscus and anomaly effects turned out to be of minor importance. Facilities for a correction of the measured differential weight analogous to the approach used by the analog Cambridge controller have been provided, though.

Buoyancy compensation requires that an "image" of the crystal be kept within the CGCS, and updated periodically. The volume of the crystal immersed in the encapsulant, and/or its diameter at the surface of the boric oxide melt, affect the calculated diameter of the currently grown portion, the crucible position setpoint, and the computed length of the grown crystal. The actual growth rate is determined by the seed lift speed and any uncompensated drop of the semiconductor melt.

Special provisions were made for the final stages of the growth run where the semiconductor melt tends to recede from the walls of the crucible due to surface tension. In this regime, the level of the melt inside the crucible remains almost constant but the diameter of the disk formed by the melt shrinks while more material is being solidified. Since the gap opening between the semiconductor melt and the crucible wall is filled up with the boric oxide encapsulant, the amount of the crystal immersed in boric oxide, and hence the buoyancy force, decreases; simultaneously, the growth rate is reduced due to an overcompensation of the melt drop by the crucible lift. The standard diameter evaluation algorithms are therefore no longer valid in the melt recession regime; hence, the CGCS was designed to allow a smooth transition between the standard and the melt recession diameter calculation modes. (This diameter control technique, in conjunction with the advanced heuristic approaches discussed below, permitted for the first time to grow crystals without the flash-out next to the tail which can hardly be avoided on a puller controlled by the conventional analog system; compare Fig. 9.)

4.3 Operation Modes Of The CGCS Software

The CGCS software comprises four levels of control each of which is an inclusive set of the preceding ones:

(1) Monitoring: All measured signals are continuously displayed on a fixed console screen (compare Fig. 2), next to their respective setpoints if applicable. The currently grown diameter of the crystal is calculated with the algorithms described above. All data on display can optionally be recorded on disk; the interval between two data records can be chosen to lie between one and 255 seconds. No actual growth control is performed by the digital system in this mode.

(2) Emulation of the analog controller's functions: While the puller was run by the analog controller in the Monitoring mode, the digital CGCS is in charge at this and at all higher levels. Depending on the sub-mode chosen, various degrees of closed-loop control are possible. In the most elementary "manual" mode, each parameter can be controlled independently. Other modes permit closed-loop diameter control with or without anomaly compensation, and, in addition, closed-loop control, of the crucible lift speed.

Setpoints may be changed instantaneously or "ramped" gradually between their current and their intended final values; the duration of the ramp is virtually unlimited. Accordingly, a "current" and a "final" setpoint value are displayed on the console for each of the "primary" parameters, namely, crystal diameter, heater temperatures, motor speeds, and power limit.

In addition to these primary parameters, an arbitrary number of internal parameters ("variables") may be identified with symbolic names, and displayed and modified under operator control. The "ramping" feature is available for these data as well; up to 20 primary parameters and variables may be "ramped" simultaneously in the current CGCS version. Since the table of the symbolic variable names is kept outside the program proper in a disk file, there is no limit to their number other than the capacity of the disk, and the time needed for reading the file. Parameters which control the operation of the system (like PID controller parameters) can be easily accessed in this way, and modified dynamically if required. On the other hand, intermediate results can be approached by their symbolic names, too, and used in the decision-making process (see below).

(3) Programmed operation: All operator entries pertaining to the actual crystal growth can optionally be recorded on a disk file, each tagged with the time (relative to the beginning of the recording) when it was issued. These "Macro" command files can be edited after the growth run (or created from scratch) with a special Macro command

editor, and used as an input for a future run where the recorded commands are executed exactly with the timing with which they were recorded. This approach permits to repeat command sequences precisely, thus off-loading the operator from routine entries, improving the reproducibility of the process (because manually entered commands can never be issued with such accurate timing), and reducing the hazard of operator errors. Command entry on the console is still possible while a Macro command file is being executed; the resulting stream of commands can be recorded in a new Macro command file, which gives the CGCS kind of a learning ability. A Macro command may even invoke another Macro; complex operations may therefore be automated (however, purely deterministically) by concatenated Macro commands.

Essentially, the Macro feature is very similar to most automation approaches applied to crystal growth to date. All commercial "automatic" systems use pre-defined changes of process parameters which are executed blindly by the controller. Experience gathered with the digital controller for silicon Czochralski growth [11],[12] indicated that a crystal growth process cannot be run in its entirety according to a rigid pre-defined scheme, for the reasons already mentioned above, and that it requires therefore frequent interactions by a human operator. The system developed at ASU is the first which endeavors to replace the operator's judgment with internally generated decisions.

(4) "Intelligent" growth control: As a simple first step of built-in decision making, the CGCS is capable of starting the execution of a Macro command file if and when a specified parameter meets a certain condition (e.g., if it assumes a value greater than or equal to a given constant). Such "Conditional Macro" commands can be posted at any time during a growth run, either by the operator or by other Macro commands; the respective conditions for their execution are checked periodically. A command is removed from the queue of pending Conditional Macros either if its condition is fulfilled and it can be executed, or if it is cleared explicitly. Albeit simple, this approach permits virtually totally automated crystal growth: Macro commands can be concatenated conditionally now, which allows to start the command sequence for a new stage of the growth process exactly when necessary. Auxiliary Macro commands can be used to support the action of the deterministic PID-based control loops either by detecting genuine emergencies and taking appropriate measures, or even by constituting a superimposed non-linear control loop.

The introduction of the "Macro" and "Conditional Macro" features resulted in an additional very important consequence: The actual growth know-how is, unlike in earlier crystal growth automation approaches, no more located within the controller program proper, but in the external Macros which can be modified and adapted to various demands much more easily than the bulk of a growth control program. Since Macro commands can be used for modifying any arbitrary system parameter (via its symbolic "variable" name), process controller parameters may be changed dynamically if and when required, depending on the current needs of the process, which permits adaptive control approaches. In fact, the same CGCS program supported by a different set of Macro command files could be used for growing gallium arsenide crystals with totally different characteristics, or even for growing crystals of any other material in any puller which is at least similar to the one for which the system was designed.

5. Experimental results:

The first operational version of the CGCS was finished around the end of 1985, and implemented on a Cambridge Instruments CI 358 puller for charges up to 8 kg. (For pecuniary reasons, the puller is currently operated with 4 kg charges only.) Meanwhile, more than thirty-five 3 inch GaAs crystals have been grown at ASU under digital control. After the basic operating parameters had been established first experimentally and also from simple estimations, an excellent overall process yield could be obtained. More than 75 percent of the recent 20 ingots were excellently shaped single crystals, with fluctuations of the nominal 80 millimeters diameter in the order of 1.5 mm or less. A typical crystal grown under autonomous digital control is shown in Fig. 9. Since a tighcer diameter control permits growth at a smaller nominal diameter without the hazard of getting under-sized portions of the crystals, boules with longer bodies can be obtained from the same charge. This results in a larger number of usable wafers, which further increases the process yield.

All crystals produced during the last year were grown virtually automatically. Operator interactions were generally limited to the starting of the heating sequence, and the starting of the seeding procedure. (The "automatic" analog controller supplied by Cambridge Instruments requires about 20 hours of continuous operator interactions during a 36 hours growth run.) Specifically, the very complex seed dipping sequence can now be done reproducibly by the CGCS on its own, despite surprisingly large variations of the actual seeding temperatures. The excellent reproducibility of the digitally controlled process could be demonstrated, among others, in two subsequent runs which resulted in crystals with a total weight of 3680 and 3681 grams, respectively. Fig. 10 shows the diameters of two crystals as a function of their lengths as computed by the CGCS. With the exception of minor differences during the cone section, the shapes of the crystals are virtually identical.

Structural and electrical measurements of digitally grown semi-insulating GaAs crystals indicate average dislocation densities ranging from $7 \cdot 10^3$ cm^{-2} at the top of the body to $1.7 \cdot 10^5$ cm^{-2} at the end of the tail, in a portion of the crystal which frequently turns polycrystalline in conventionally grown crystals. Dislocations due to slip are practically absent over the entire crystal body. Macroscopically, dislocations form a characteristic "X"-shaped pattern on the surface of a (100) wafer; microscopically, they are arranged in a cellular structure throughout the entire crystal, with a cell size of 300 to 500 μm, and with cell walls composed of edge dislocations. Electrical characteristics were found to be exceedingly uniform; on a wafer cut from the tail end of the body, for example, the net carrier concentration was found to lie between $5.0 \cdot 10^7$ and $7.6 \cdot 10^7$ cm^{-3}. The carrier mobility ranged from 5200 to 5800 cm^2/Vs, and resistivity, from $1.5 \cdot 10^7$ to $2.4 \cdot 10^7$ Ωcm [14].

6. Conclusion:

A digital controller for a high-pressure LEC puller for gallium arsenide has been developed at Arizona State University. This controller combines conventional deterministic control approaches with advanced heuristic methods, permitting an essentially fully automated growth process. The yield of the digitally controlled process is significantly superior to the yields obtainable with the conventional approaches; according to recent characterization results, the crystals grown with the digital controller are substantially more uniform than those grown with the analog controller.

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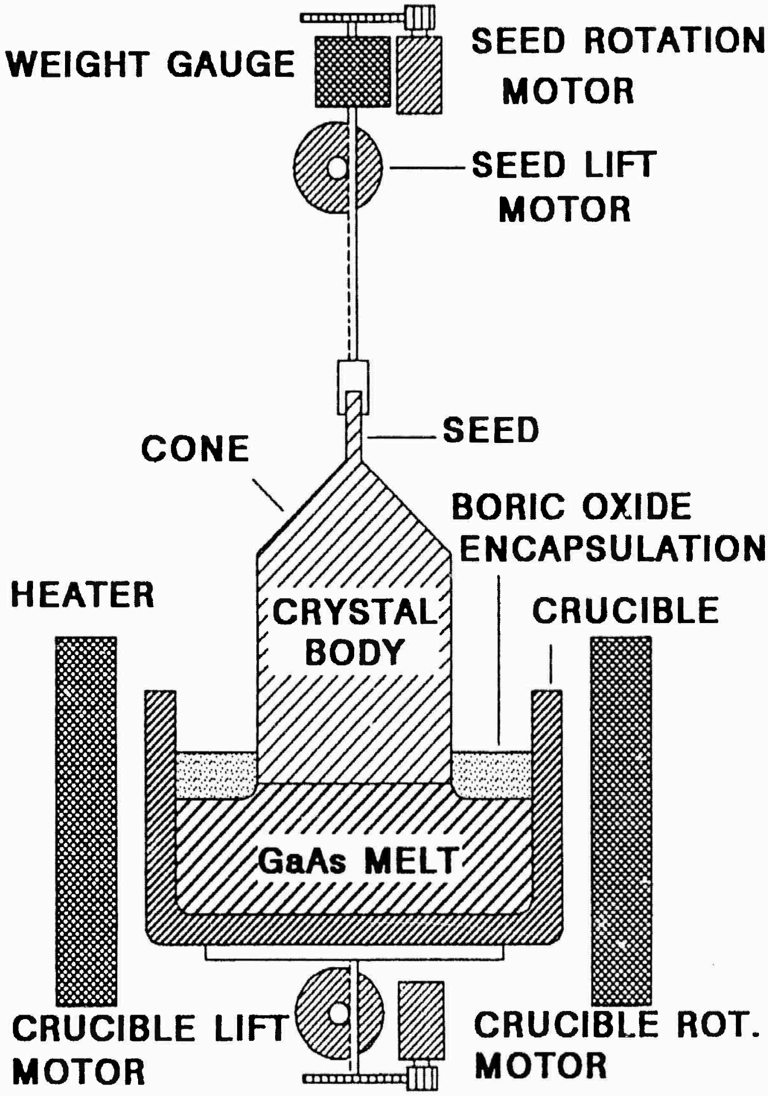

Fig. 1: Main components of an LEC crystal puller.

```
08-10-87  21:19:54  Run ID: Demonstration Screen  MACRO   System Time: 27:16:22
--------------------------------------------------------------------------------
                     Actual:   Setpoints:    | Mode: Automatic       Length:    85.45
Diameter (D):        83.73     82.00   82.00 |
                                             | Ramping:     2/20     Condit.:    1/8
Temp. 1 (T1):        23.65     23.63   23.50 |
Temp. 2 (T2):        23.98     23.95   23.80 | Weight:     2348.     Diff.Wt.:  1.476
Temp. 3 (T3):        23.39     23.36   23.25 | Seed Pos.: 246.7     Cruc.Pos.: 23.89
                                             | Base Temp: 20.19     Gas Press: 297.6
Power Limit (PL):              80.00   80.00 ----------------------------------------
                                             |                 Actual:   Setpoints:
Seed Lift (SL): 9.003          9.000   9.000 | Seed Rot. (SR): 4.997     5.000   5.000
Cruc Lift (CL): 1.487          1.492   1.500 | Cruc Rot. (CR): -30.0     -30.0   -30.0
--------------------------------------------------------------------------------
Power In/Out:    47.37/45.29      49.12/48.28      45.40/42.12      Contact: *32*
--------------------------- ----------------------------------------------------
28B1H=    -28         28C9H=    -31        2842H= 0.001250   36F9H= 23.67148
set prop10 -20 300
macro
***** Executing Macro MACRO  *****
deb c rcrset 4
Please Command:
comm This is a demonstration screen with arbitrarily invented data_
```

Fig. 2: Console screen display of the Czochralski Growth Control System.

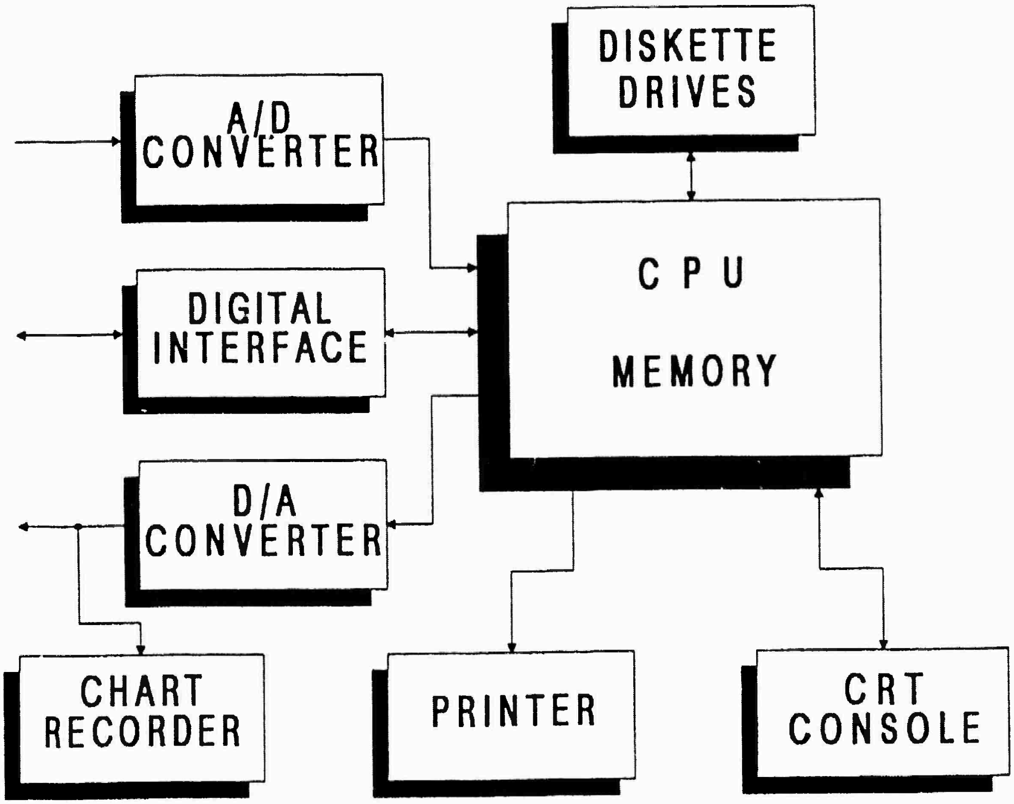

Fig. 3: Block diagram of the digital controller.

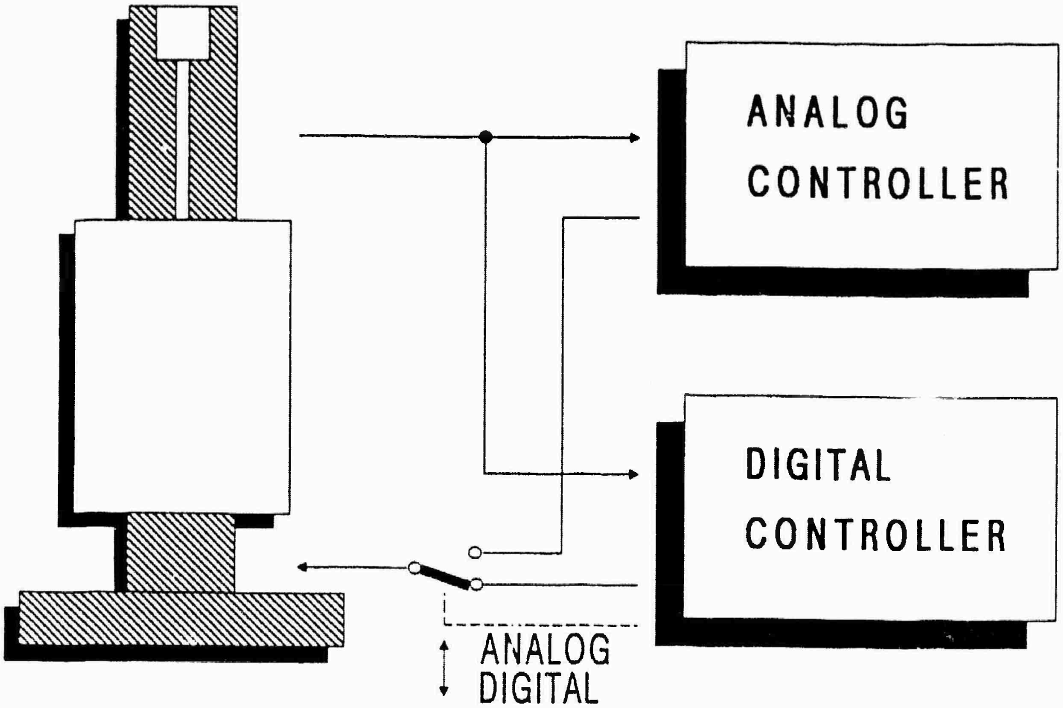

Fig. 4: Implementation of the digital controller.

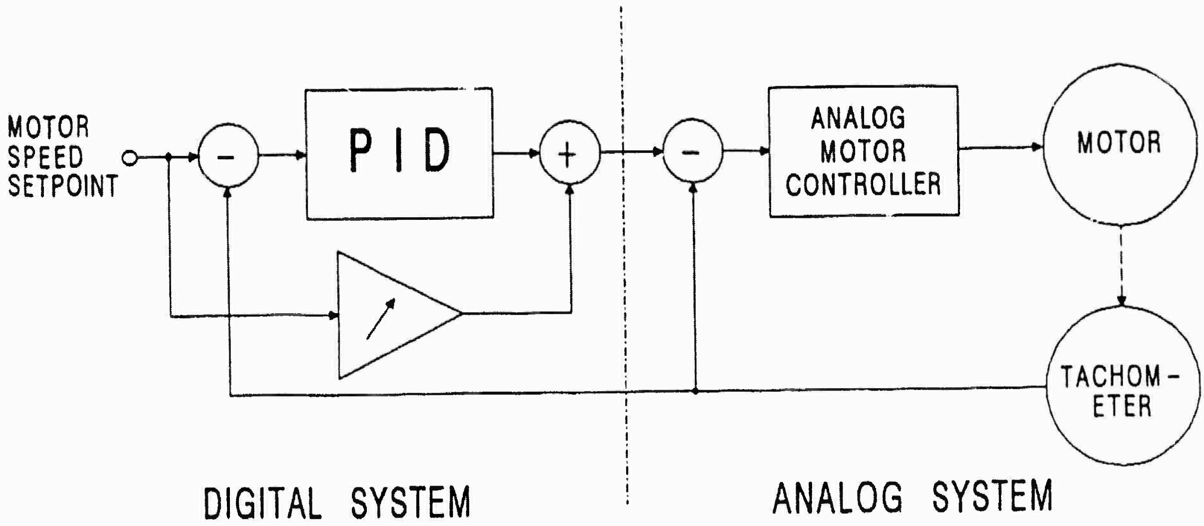

Fig. 5: Control loop for one of the four motors in the CGCS (analog/digital and digital/analog conversion are not explicitly shown).

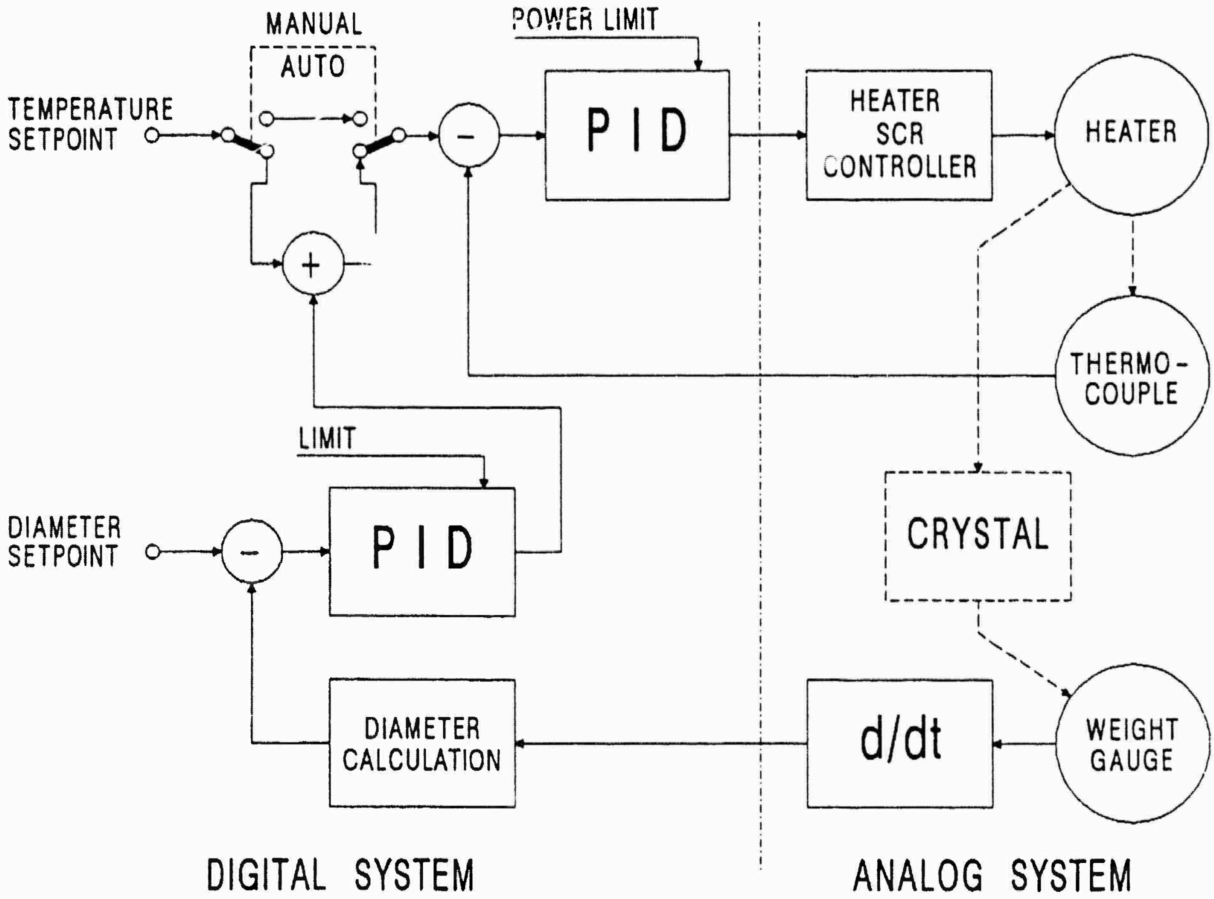

Fig. 6: Heater temperature and crystal diameter control loops (analog/digital and digital/analog conversion are not explicitly shown).

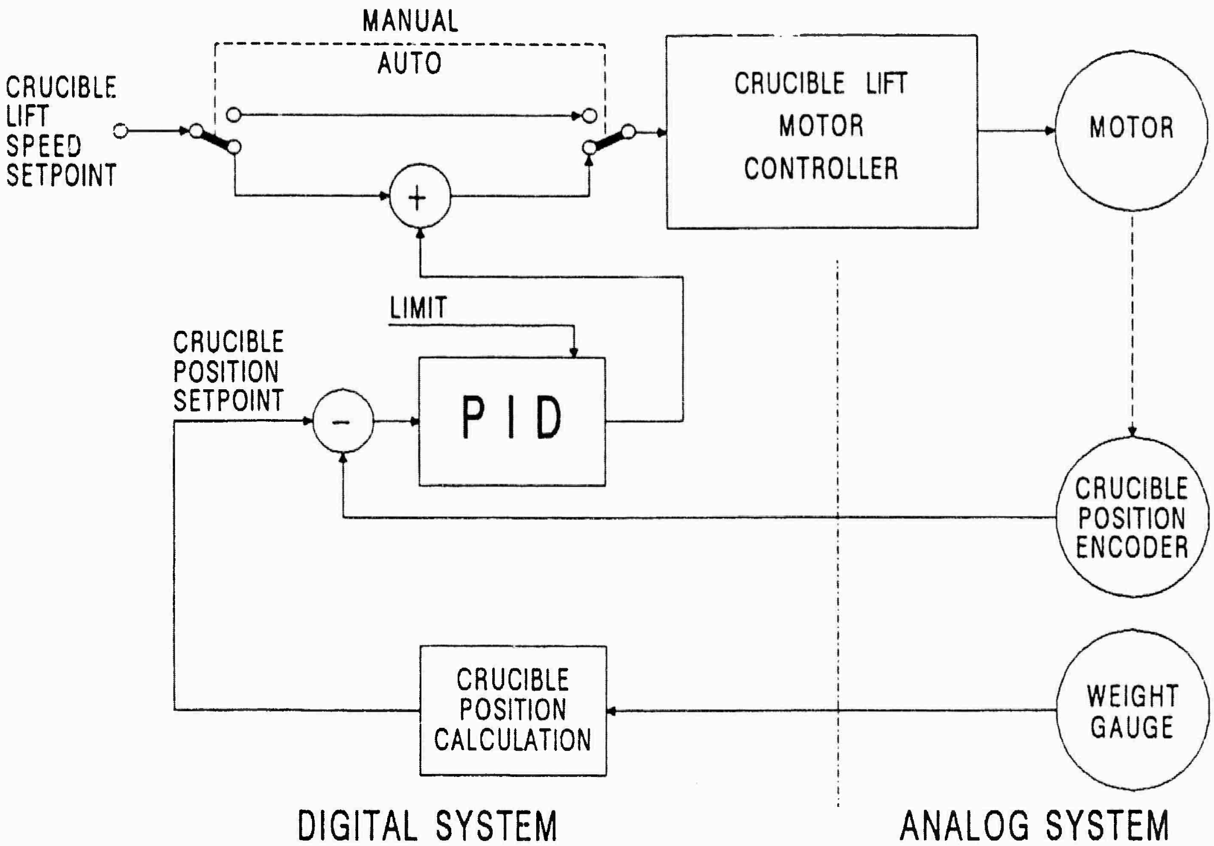

Fig. 7: Crucible position control loop (analog/digital and digital/analog conversion are not explicitly shown).

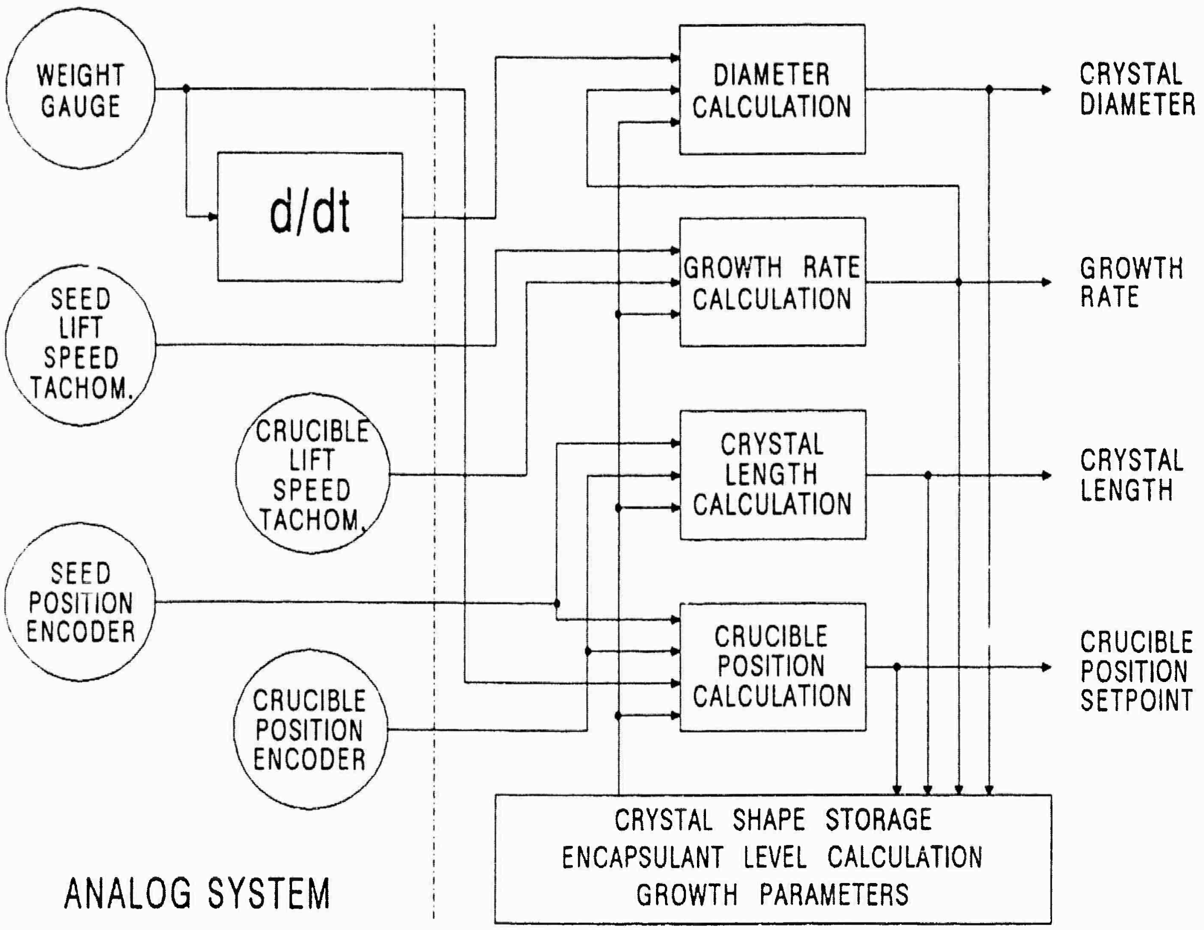

Fig. 8: Block diagram of the evaluation algorithms for the crystal diameter, the growth rate, the crystal length grown, and the crucible position setpoint (analog/digital and digital/analog conversion are not explicitly shown).

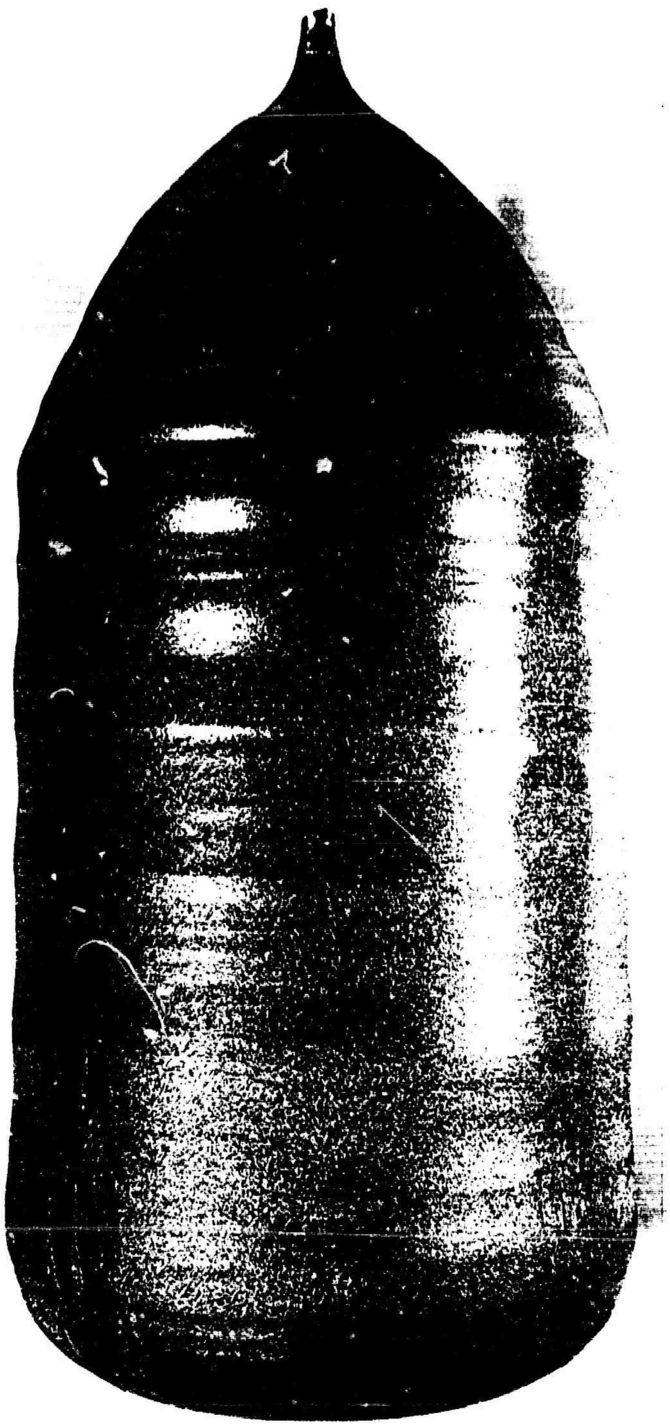

Fig. 9: Typical 4 kg, 3" GaAs crystal grown with the CGCS.

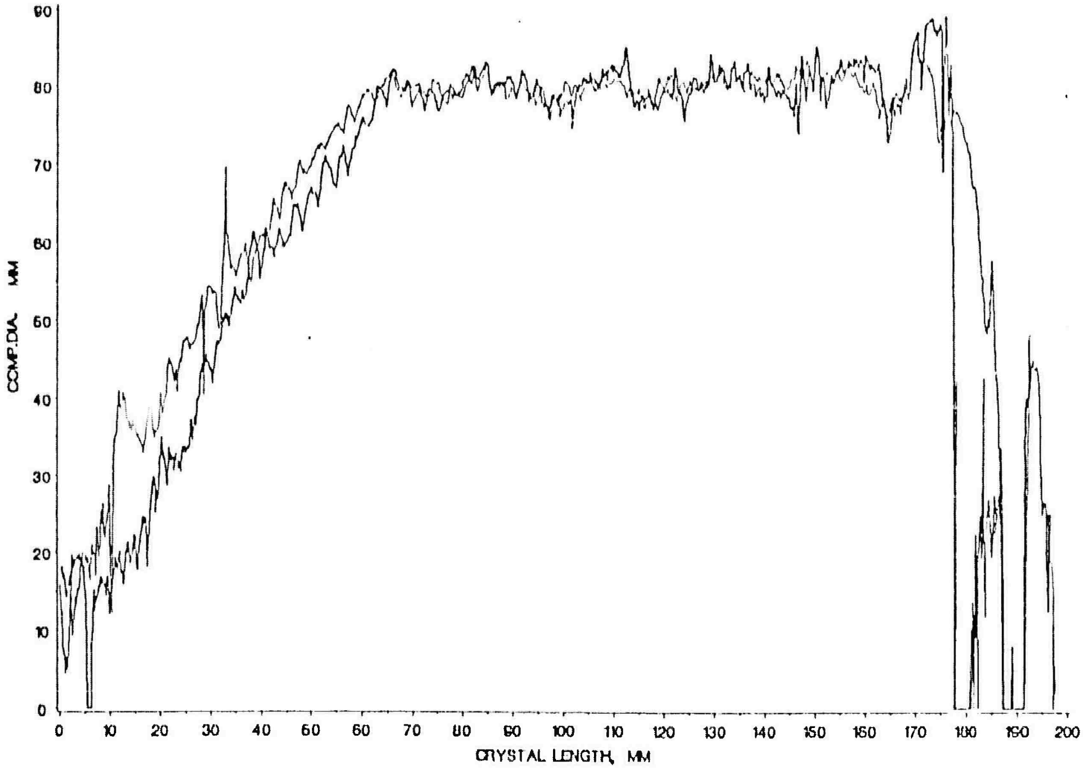

Fig. 10: Reproducibility of crystal shape shown for two crystals, D18 and D20: Computed diameter as a function of crystal length.